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Abstract

Heavy-ion fusion (HIF) designs for inertial fusion energy (IFE) power plants typically require final focusing magnets just outside the reaction chamber and blanket. Due to penetrations within the chamber and blanket, the magnets are exposed to a radiation environment. Although the magnet bores would be sized to avoid line-of-sight irradiation, the magnets still would be susceptible to nuclear heating and radiation damage from neutrons and γ-rays. Additionally, the magnets must be included in waste management considerations due to neutron activation. Modified versions of the HYLIFE-II IFE power plant featuring two-sided illumination by arrays of 32 or 96 beams from each side are presented. A simple, point-of-departure quadrupole magnet design is assumed, and a three-dimensional neutronics model is created for the Flibe pocket, first wall, blanket, shield, and final two focusing magnets. This work details state-of-the-art neutronics calculations and shows that the final focus system needs to be included in the economic and environmental considerations for the driver-chamber interface of any HIF IFE power plant design.

1. Introduction

Designs for IFE power plants utilizing heavy-ion drivers typically use an array of magnets to focus the beams to the center of the target chamber. These magnets would be subjected to significant levels of neutron and γ-ray radiation. The design of such systems must incorporate adequate shielding to ensure that the magnets do not quench (if superconducting coils are used), do not fail in an unreasonably short length of time, do not require an unreasonably large amount of cooling, and do not pose an unreasonable burden from a waste management perspective. While previous work has attempted to address some of these issues, some of the work is incomplete or impractical given recent trends towards a greater number of beams and a smaller half-angle of the array of beams.[1-2] The present work updates and expands upon these previous analyses by considering two baseline final focusing magnet designs–one with 32 beams per side and another with 96 beams per side. Nuclear heating, radiation damage, and neutron activation results are presented for each.

2. Previous work

Past design studies typically considered drivers with as many as 20 beams and as much as 30-40 cm of shielding on the inner bore of the final focus magnets.[1-2] Current thinking, however, calls for a greater number of beams and smaller half-angles to accommodate target designs and thick-liquid wall protection schemes. These designs will require significantly smaller magnets, and thus, less shielding.

Due to the symmetry of most designs and the complexity of magnet shielding calculations, previous work has often resorted to modeling only a portion of the reactor geometry.[1] If done correctly, this is an acceptable approach. Only planes, however, can be used to create such models–one cannot use conical reflectors.[3] Such "ice-cream cone" models bias the results in an unpredictable manner and should not be used.

3. Final focus neutronics model

A neutronics model has been created for the final focusing magnets in a modified version of the HYLIFE-II power plant design.[4] In HYLIFE-II, thick-liquid jets of Flibe are used to provide line-of-sight shielding for the first wall. Despite this, neutrons and γ-rays may stream up the beamlines towards the focusing magnets. HYLIFE-II originally called for single-sided illumination by only 12 beams. Here, two modified versions of the design are analyzed. *Figure 1* shows a view of the 64-beam neutronics model. The array of 32 beams is created from a 6×6 grid with the corners removed. In this first version of the model, each magnet was modeled as a homogeneous mixture of the actual materials. In later versions, one set of magnets was modeled with the detailed radial build.

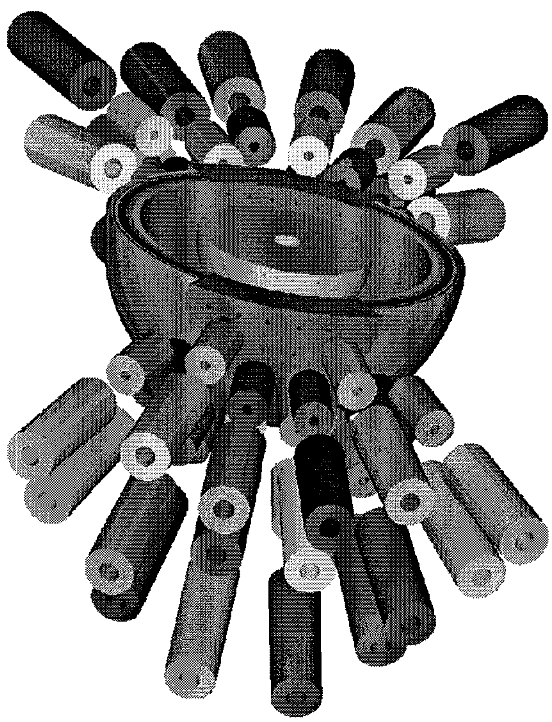

Fig. 1. Shown are the last two quadrupole magnets, blanket, chamber, and Flibe pocket. The magnets are staggered to provide a smaller half-angle.

Using this model, the final focus design has been evaluated for nuclear heating, radiation damage, and waste management. Small improvements have been made in successive versions of the model and the calculation has been repeated.

Following a series of calculations with the 64-beam models, a 192-beam model was created. This design uses a more aggressive (smaller) magnet design, and thus, the array half-angle is about the same as in the 64-beam case. Each array is formed from a 10×10 grid with the corners removed. The final three sets of magnets are included in the model, whereas only the last two magnets were included in the 64-beam models. Due to difficulties in obtaining a sharp edge on the Flibe jets, the 192-beam case also uses Flibe vortices (the 64-beam cases assumed a *perfect* edge to the Flibe jets). The vortices would extend ~ 70 cm into the chamber, and it would make it possible to get the Flibe closer to the beamlines, and thus, provide better shielding.

The radial build for the quadrupole magnets used in the 192-beam cases is shown in *table I.* A similar radial build was used in the 64-beam cases. The radial build is important not only for flux and subsequent neutron activation calculations, but it is needed to determine the power needed for magnet cooling. The power required to remove 1 watt depends upon the temperature of the region. Here, we assume a penalty of 2:1 for water- or gas-cooled regions, 20:1 for liquid nitrogen cooling (LN_2), and 200:1 for liquid helium (LHe) cooling.

4. Results

Results are presented for the various indices as ranges for the various versions of the two basic (64- and 192-beam) models. In all, nine different versions of the 64-beam model and three versions of the 192-beam model have been analyzed.

4.1 Nuclear heating and cooling

To ensure the magnets remain superconducting, energy deposited by radiation must be removed. Two constraints apply here. First, the nuclear heating from a single shot must not quench the magnet in a prompt manner. Second, the integrated heating and the power required to cool the magnets must not be excessive. The first constraint can be met as long as the energy deposited in the coils and stabilizer are less than ~ 100 mJ/cc.[5] The second constraint is more subjective. In theory, a large cooling power can be accommodated, but it will adversely affect the economics of the power plant.

Table I. The radial build for the small quadrupole magnets in the 192-beam case.

Component	Inner radius/thickness
Inner bore	0-8.70 cm/tapers to 5.9 cm at front; gap filled with tungsten
SS316 beamtube	8.70/0.32 cm
He gas coolant	9.02/0.32 cm
SS316 casing	9.34/0.16 cm
Vacuum/insulation	9.50/1.00 cm
Tungsten shielding	10.50/0.25 cm
He gas coolant	10.75/0.31 cm
Tungsten shielding	11.06/0.125 cm
Vacuum/insulation	11.185/1.00 cm
Tungsten shielding	12.185/3.125 cm
LN_2 coolant	15.31/0.60 cm
SS316 casing	15.91/0.16 cm
Vacuum/insulation	16.07/1.00 cm
SS316 casing	17.07/0.25 cm
NbTi + Cu coils + LHe coolant (45/45/10)	17.32/2.00 cm
SS316 casing	19.32/0.36 cm

In the 64-beam cases, the nuclear heating in the coil regions of the closest magnet range from 1.6-2.6 $\times$ 10^{-4} J/cc. The 192-beam cases resulted in higher levels of heating: 1.0-3.4 $\times$ 10^{-3} J/cc. In addition, one must consider the decay heat of the magnets. In the 64-beam cases, the volumetric afterheat in the coils ranges from 3.8-5.4 $\times$ 10^{-5} W/cc. In the 192-beam cases, the activation is higher, and the afterheat is 2.2-5.2 $\times$ 10^{-4} W/cc. In all cases, the afterheat is small compared to the "prompt" nuclear heating.

The power required to cool the magnets has been estimated given the heating rates and the cooling efficiencies mentioned above. In the 64-beam cases, the cooling varies from 12.4 to 18.0 MW. In the 192-beam cases, the power varies from 8.3 to 21.1 MW. It should be noted, however, that the 192-beam quadrupole design does not include insulation or a coil clamp outside the coils. This concept is only viable if an external structure provides the support. Due to the lack of insulation, this structure would also have to be cooled to LHe temperatures. Calculations estimate that this structure would require 58 MW of cooling. Redesign of these quadrupoles and support structures may be warranted.

4.2 Radiation damage

Radiation damage limits for conductors, stabilizers, and insulators are highly uncertain. Data is sparse and does not always replicate the conditions (e.g., temperature) as they would exist in an operating magnet. Nevertheless, calculated values are compared to available data. In HIBALL-II study, a dose limit of 5 $\times$ 10^7 Gy was proposed for polyimide insulators, while 4 $\times$ 10^6 Gy was given for epoxies.[1] In the 64-beam cases, dose rates of 4.2-6.9 $\times$ 10^6 Gy/y were calculated. Higher levels of 3.0-9.9 $\times$ 10^7 Gy/y were observed in the 192-beam cases. These are total doses. In all cases, the doses are ~ 90% from γ-rays.

Experimental results using the RTNS-II facility were reported in two other papers. Van Konynenburg et al. report a 2.4% increase in the resistivity of Cu irradiated to a fluence of 2 $\times$ 10^{17} n/cm^2.[6] Hahn et al. report a 2x reduction in the critical current density and a 3 K drop in the critical temperature for Nb_3Sn at a fluence of 2 $\times$ 10^{18} n/cm^2.[7] Calculated fluences in the coils ranged from 1.9-2.7 $\times$ 10^{18} n/cm^2 in the 64-beam cases and 1.7-3.4 $\times$ 10^{19} n/cm^2 in the 192-beam cases.

The HIBALL-II study suggests a "most conservative" limit of 4 $\times$ 10^{-5} dpa/y for the displacement rate in the coils.[1] This limit is based upon a 5 year exposure followed by room temperature annealing. The calculated dpa rate in the Cu stabilizer in the 64-beam cases was 1.4-2.3 $\times$ 10^{-3}

dpa/y. Displacement rates were not calculated for the 192-beam cases.

4.3 Neutron activation

Neutron activation of the quadrupole magnets is significant. Contact dose rates from the NbTi and Cu prohibit even remote maintenance activities for an extended duration. Following 3 years of irradiation, the decay of ^{60}Co keeps the contact dose rate above the recycling limit of 100 mSv/hr for 2-3 y. Beyond ~ 10 y of cooling, dose rates are dominated by the decay of ^{94}Nb (20,000 y half-life). In the 192-beam cases, the dose rate stays near 160 mSv/hr for thousands of years. Switching from NbTi to Nb_3Sn will not help as ^{94}Nb is produced from natural Nb.

Given difficulties that may occur in recycling the magnets, waste disposal appears to be of great importance. The ^{94}Nb, however, also has a serious effect on the waste disposal rating (WDR) of the coils. The WDR varies from 35 to 52 in the 64-beam cases and 380 to 570 in the 192-beam cases. Given that the WDR >> 1 in all cases, it appears that the coils would need to be disposed of via deep-geologic disposal unless significant improvements are made to the magnet shielding design. The waste volumes are comparable in the two designs. In the 64-beam cases, the total volume of conductors and stabilizers is ~ 85 m^3. Although the 192-beam cases have much smaller coils (5 m^3 total), the dose and fluences experienced by the coils are ~ 10-20× higher, and thus, the lifetimes are likely to be 10-20× shorter. Therefore, the life-cycle waste volume would be 50-100 m^3 in the 192-beam cases.

5. Conclusions and future work

Shielding of final focusing magnets is a serious issue for HIF power plant designs. The results presented here are for modern final focus designs that incorporate significantly less shielding than previous designs. Nuclear heating, including that from activation, appears to be manageable. The cooling power in some of the designs, however, is as high as 6-7% of the total electricity produced by the power plant. Improvements will be made to the designs and reported in future publications.

Radiation-induced effects/damage may be problematic for the current designs. The limited data suggest that magnet lifetimes may be as short as 0.5-3 y. Data taken under realistic conditions are needed.

Excessive neutron activation makes recycling of magnet coils problematic. The production of ^{94}Nb also makes disposal via shallow land burial appear impossible without large improvements to the shielding design. The waste volumes involved are comparable to those from the first wall and blanket for HYLIFE-II.

Future work must strive to increase the shielding effectiveness of final focus designs and reach a balance between performance, economics, and environmental considerations.

Acknowledgments

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